

# The beginning of cosmic ray astronomy

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## Abstract

We discuss the anisotropic arrival directions of the ultra high energy cosmic rays detected by Auger which I consider one of the biggest discoveries in astrophysics during the last year.

## 1 Introduction

As you may conclude from the different concluding remarks at this meeting there are various approaches to doing them. Most of my esteemed colleagues spoke on several topics that they consider important now and in the future. I decided to concentrate on one single topic that excited not only me but a large number of astrophysicists that were never interested in ultra high energy cosmic rays (UHECR) - the observed correlation of the highest energy events detected by the Pierre Auger Observatory in Argentina with active galactic nuclei (AGN) [1, 2]. This discovery marked the beginning of a new type of astronomy - cosmic ray astronomy - that may become as important in the future as the TeV gamma ray astronomy has recently become.

TeV gamma ray astronomy does not only reveal the type of the gamma ray sources, it also provides an indirect measurement of the infrared/optical background whose estimates are based on theoretical calculations involving the light emission of different types of stars and galaxies and the cosmological evolution of these objects and the matter density around them in the Universe. Cosmic ray astronomy also involves some general features of the nearby Universe that are otherwise extremely difficult to measure such

as the local (within 200 Mpc) distribution of matter and different powerful astrophysical objects, the average strength of the intergalactic magnetic fields (that could even be mapped when the sources are confirmed) and the galactic ones.

I will discuss these results and report on the small contribution that I have made to this topic. It is not connected to the type of the UHECR sources, but includes a better than  $3\sigma$  confirmation of the anisotropy detected by Auger [3].

## 2 The anisotropy discovered by Auger

The Auger Collaboration reported a correlation of their 27 highest energy events ( $E > 5.7 \times 10^{19}$  eV (57 EeV) with active galactic nuclei (AGN) at redshifts  $z$  less than 0.017 [1, 2] from the Vèron-Cetty and Vèron catalog [4] (V-C). Twenty out of 27 events are within  $3.1^\circ$  of individual AGN, while for isotropic arrival distribution one expects on average 5 coincidences. Five of the non-correlating events come from less than  $12^\circ$  galactic latitude which may be understood as larger deflections in the galactic magnetic field. The scattering in the galactic magnetic field is consistent with these events being protons, not heavier nuclei. It is surprising that there are no events coming from the direction of the Virgo cluster, that includes a large number of powerful galaxies in addition to M87, as stated in Ref. [5].

A better description of the statistical analysis and a broad discussion of its features is given in the longer second paper [2]. The self correlation between the 27 events was studied and found to be consistent with the existence of many (more than 61) sources within the 71 Mpc radius, that leads to a source density of  $3.5 \times 10^{-5}$  Mpc $^{-3}$ . The Auger Collaboration warns us that because most of the correlating AGN are not very powerful the observed anisotropy may be due to a different type of source.

It is quite interesting that two Auger events coincide with the close by (less than 4 Mpc) powerful radio galaxy Cen A, and several other events are close to it.

Among the criticism toward this analysis is the statement that redshift  $z$  of 0.017 is much lower than the expected contribution of redshifts for extragalactic protons and nuclei. Protons are supposed to come to us from redshifts up to 0.05, roughly distances to 200 Mpc. Other authors complain about the types of AGN in the V-C catalog that are low luminosity Seyfert and LINER galaxies. Since I do not have much knowledge about AGN I decided to check the discovered anisotropy by studying the correlation of

the Auger events with the Supergalactic plane (SGP).

### 3 Correlation of the Auger events with the Supergalactic plane

A report on the correlation of the then existing statistics of UHECR of energy above  $4 \times 10^{19}$  eV with the Supergalactic plane [6] was published in 1995 [7]. The data set consisted mostly of events detected by the Haverah Park detector with the addition of events detected by AGASA, Yakutsk and Volcano Ranch air shower arrays. The anisotropy of that data set was studied by a comparison of the average and RMS supergalactic latitudes  $|b_{SGP}|$  of the experimental events to that of an isotropic Monte Carlo sample. The significance of the correlation was at the  $3\sigma$  level. Later on, when the AGASA detector dominated the world's statistics, the significance of the correlation decreased. We decided to check on the correlation of the

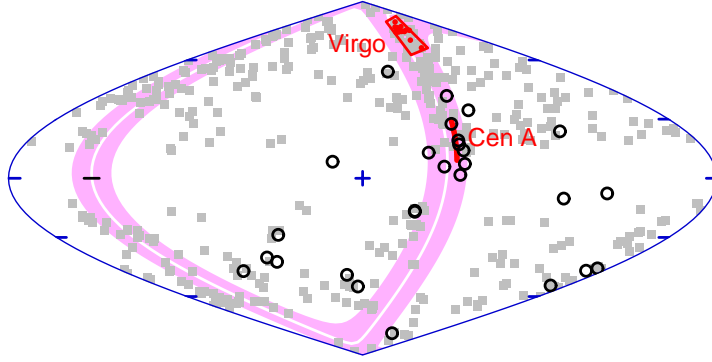


Figure 1: The 27 Auger events are superimposed in galactic coordinates in a sinuoidal projection on the supergalactic plane in the definition of Ref.[6]. The shaded area shows  $|b_{SGP}| < 10^\circ$ . The gray squares show the positions of V-C AGN that have galactic latitude more than  $12^\circ$ . The Virgo cluster and Cen A are also shown.

27 Auger events with the same definition of the nearby large scale mass distribution. The result is shown in Fig. 1. The probability for such a correlation was calculated with a Monte Carlo simulation where 100,000 sets of 27 events were injected isotropically in the Auger field of view. We arbitrarily chose to bands of  $10^\circ$  and  $15^\circ$  in supergalactic latitude that surround the  $1\sigma$  deviation of the AGN from the V-C catalog to the SGP. Nine (13) of

the 27 experimental events fall in these two bands. The random coincidence probability derived from the Monte Carlo is 0.024 (0.008) corresponding to 2.0 (2.4)  $\sigma$ .

Until now we dealt with the original definition [6] of the supergalactic plane by de Vaucouleurs. This definition was studied in 2000 by Lahav et al. in terms of redshift [8] on the basis of the Optical Redshift Survey (ORS) (8457 galaxies, 98% with redshift). Since ORS had a zone of avoidance of  $|b| < 20^\circ$  it was complemented with IRAS galaxies in order to describe better the intersection of SGP with the galactic plane. This study introduces correction to the definition of SGP for different distances from 0 to 80 Mpc. The one that is most suitable for analysis of the Auger events is for distances up to 70 Mpc, i.e. identical to the redshift of 0.017. The corrected shape of the SGP is plotted in Fig. 2 the same way as the original definition is plotted in Fig. 1.

One can now count how many UHECR are in the  $10^\circ$  and  $15^\circ$  band with the new definition of the supergalactic plane. The numbers are 13 and 15 events respectively. The probability to have so many events from

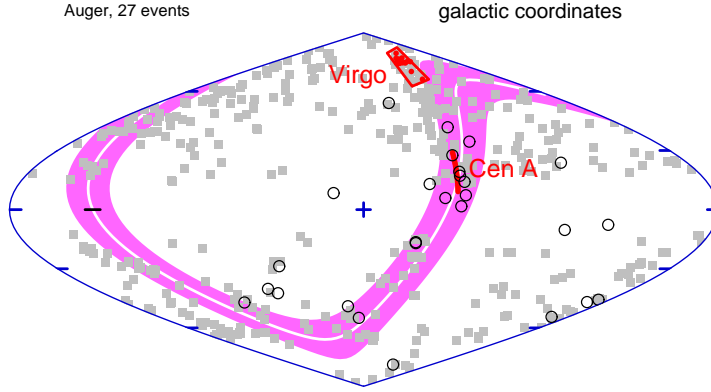


Figure 2: The supergalactic plane corrected as in Ref. [8] for distances up to 70 Mpc.

isotropic arrival direction distribution drops to  $1.6 \times 10^{-4}$  ( $6.0 \times 10^{-4}$ ) for distances from the supergalactic plane of  $10^\circ$  ( $15^\circ$ ). The correlation of the Auger events with the updated definition of the SGP within 70 Mpc is indeed much more significant - the probabilities above correspond to  $3.6(3.2)\sigma$ . Since the rotation angle of SGP in galactic coordinates in the analysis of Lahav et al. depends on the the redshifts of the astrophysical objects the one we used certainly defines better the plane of weight of the mass distribution

within 70 Mpc and of the UHECR sources if these cosmic rays indeed are produced within this distance. Even if the GZK horizon is larger we expect some degree of correlation with the nearby astrophysical objects.

It is important to note that the HiRes Collaboration does not confirm the correlation with AGN [9]. Out of 13 highest energy events only two correlate with AGN from the V-C catalog within  $3.1^\circ$ . The HiRes paper does not describe well their field of view and it is difficult to understand if the difference in the field of view is the reason for this discrepancy. There is also a lack of obvious correlation with SGP. Three (5) of the HiRes events are within  $10^\circ$  ( $15^\circ$ ) of the SGP in the definition of Ref. [8].

We still believe that the anisotropy published by the Auger Collaboration is strong and with the increase of the experimental statistics, which must have doubled by August 2008, it will lead us to identification of the sources of the highest energy cosmic rays.

## References

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